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AD-A225 195

# ANALYSIS OF THERMAL PROCESS OF LOW- AND HIGH-ACID FOODS IN SEMIRIGID CONTAINERS

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AUGUST 1990

FINAL REPORT  
NOVEMBER 1987 - DECEMBER 1988

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| REPORT DOCUMENTATION PAGE  |       |  |   | Form Approved<br>OMB No. 0704-0188                   |   |
|--|-------|--|---|--|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED   |       |  | 1b. RESTRICTIVE MARKINGS  |  |   |
| 2a. SECURITY CLASSIFICATION AUTHORITY  |       |  | 3. DISTRIBUTION/AVAILABILITY OF REPORT  |  |   |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE  |       |  | Approved for public release: distribution unlimited.  |  |   |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)  |       |  | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br>NATICK/TR-90/040                                       |  |   |
| 6a. NAME OF PERFORMING ORGANIZATION<br>FOOD SCIENCE DEPT., COOK COLLEGE<br>RUTGERS UNIVERSITY  |       | 6b. OFFICE SYMBOL<br>(if applicable)     | 7a. NAME OF MONITORING ORGANIZATION<br>U.S. ARMY NATICK RESEARCH, DEVELOPMENT &<br>ENGINEERING CENTER |  |   |
| 6c. ADDRESS (City, State, and ZIP Code)<br><br>NEW BRUNSWICK, NEW JERSEY 08903   |       |  | 7b. ADDRESS (City, State, and ZIP Code)<br><br>NATICK, MA 01760-5018                                  |  |   |
| 8a. NAME OF FUNDING/SPONSORING<br>ORGANIZATION   |       | 8b. OFFICE SYMBOL<br>(if applicable)     | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>CC: 8315825207059<br>IPA Assignment Agreement      |  |   |
| 8c. ADDRESS (City, State, and ZIP Code)  |       |  | 10. SOURCE OF FUNDING NUMBER:   |  |   |
|  |       |  | PROGRAM<br>ELEMENT NO.<br>6.2   | PROJECT<br>NO.<br>IL162786                           | TASK<br>NO.<br>AH99BC<br><br>WORK UNIT<br>ACCESSION NO<br>059 |
| 11. TITLE (Include Security Classification)<br><br>ANALYSIS OF THERMAL PROCESS OF LOW- AND HIGH-ACID FOODS IN SEMIRIGID CONTAINERS (u)   |       |  |   |  |   |
| 12. PERSONAL AUTHOR(S)<br>KAN-ICHI HAYAKAWA, JIAJUN WANG, SEYMOUR GILBERT  |       |  |   |  |   |
| 13a. TYPE OF REPORT<br>Final   |       | 13b. TIME COVERED<br>FROM 11-87 TO 12-88 |   | 14. DATE OF REPORT (Year, Month, Day)<br>August 1990 |   |
| 15. PAGE COUNT<br>36   |       |  |   |  |   |
| 16. SUPPLEMENTARY NOTATION   |       |  |   |  |   |
| 17. COSATI CODES   |       |  | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)                     |  |   |
| FIELD  | GROUP | SUB-GROUP                                | RATION, PACKAGING, THERMOPROCESSING, LETHALITY  |  |   |
|  |       |  | FOOD, SEMIRIGID, TEMPERATURE, MILITARY  |  |   |
|  |       |  | THERMOSTABILIZED, CONTAINERS, SIMULTANEOUS, INSULATION (S)  |  |   |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number)<br><br>One military prototype meal consists of thermostabilized low- and high-acid foods in semirigid containers. These foods have in the past been thermoprocessed separately because of greatly different lethality requirements. In order to minimize production costs, the present study sought to examine the feasibility of simultaneously processing one meal consisting of chili con carne, white rice, and sliced peaches in syrup. The simultaneous processing was not possible by adjusting initial food temperatures according to computer-simulation using food temperature data collected experimentally. However, simultaneous thermostabilizing was possible when a container for the peach item was insulated properly with expanded polystyrene. The proper insulation thickness was slightly dependent on the z value of the target inactivation factor. |       |  |   |  |   |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br><input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS   |       |  | 21. ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED  |  |   |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>LAURIE OLEKSYK  |       |  | 22b. TELEPHONE (Include Area Code)<br>(508) 631-4555  |  | 22c. OFFICE SYMBOL<br>STRNC-WTS                               |

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## PREFACE

The following is a report on the computer analysis of simultaneous processing of high and low acid foods in semirigid containers. The Intergovernmental Personnel Act (IPA) Assignment Agreement was awarded to Food Science Department, Rutgers University, New Brunswick, New Jersey, under Project 1L162786AH99BC059. The work was completed during the period November 1987 to December 1988.

Natick Project Officers for IPA Assignment Agreement were Angela Fong and Laurie Oleksyk with Peter Burke as alternate Project Officer.

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# ANALYSIS OF THERMAL PROCESS OF LOW- AND HIGH-ACID FOODS IN SEMIRIGID CONTAINERS

## INTRODUCTION

The concept of thermostabilized food in semirigid plastic containers has been accepted by the general consumer because of the packages' easily recognizable profiles, the foods' shelf stability, and their convenience. Procedures for the thermal processes of food in those containers are described in several articles (Dahlgren, 1985; Wachtel, 1987).

A prototype tray meal consisting of an entree, a starch and dessert in semirigid containers is under consideration for some types of military feeding, for example, remote site feeding. High- and low-acid foods usually are included within one meal. These packaged food components are processed separately according to the current practice since their target process lethalties vary greatly. The simultaneous processing of one complete meal would greatly reduce the production costs of the military rations since the need for separate thermal processes would be eliminated. The objective of the present work is to analyze the feasibility of simultaneously processing high- and low-acid foods packaged in one semirigid compartmented container.

## PROCEDURES

A meal consisting of chili con carne, white rice, and peach slices in syrup was selected for the present study. The first two items and the remaining one are low- and high-acid foods, respectively.

Two approaches for accomplishing the simultaneous processing of the three stated foods were examined for the present work.

The first is to adjust initial food temperatures and retort temperatures. The second is to apply a layer of insulation to the compartment containing the peach slices, which require the least process lethality among the three. A computer program -- a modified version of one previously developed for the accurate evaluation of thermal processes (Hayakawa, 1977) -- was used to examine feasibility for the simultaneous processing of these foods. The thermal death-time parameters of the target microorganisms and the heat transfer parameters of packaged foods were required for this examination. The parameters were obtained as described below.

#### Thermal Death Time Characteristics

A target sterilizing value,  $F_p$ , should be defined for the thermal processing of each food. This value was estimated using the temperature data of each food which underwent a proper thermal process as described in Table 1 (Data were provided by the U.S. Army Natick RD&E Center). All processes were done in a still retort that was manufactured by the Berlin Food Processing Equipment Co. The heating medium was hot water pressurized with air.

The following equation was used to estimate the proper sterilizing values (Ball and Olson, 1957),

$$F_p = \int_0^{t_{\text{end}}} 10^{(T-T_r)/z} dt \quad (1)$$

where:  $t_{\text{end}}$  = Time at the end of the process

$T_r$  = Reference temperature

$z$  = Slope index of thermal death time curve

The temperature data were placed in 'T' of eq. 1 and an  $F_p$  value was estimated through numerical integration using Simpson's rule (a general method).



Table 1. Processing Conditions of Selected Food in Semirigid Containers

| Food            | Net Weight<br>g | T <sub>0</sub><br>°C | T <sub>1</sub><br>°C | P <sub>a</sub><br>x 10 <sup>5</sup> P <sub>a</sub> | t <sub>up</sub><br>h | t <sub>b</sub><br>h |
|-----------------|-----------------|----------------------|----------------------|--|----------------------|---------------------|
| Peaches         | 227 (136*)      | 24.8                 | 104.4                | 1.082  | 0.117                | 0.267               |
| White rice      | 227             | 30.3                 | 118.1                | 2.324  | 0.517                | 0.633               |
| Chili con carne | 326             | 34.2                 | 115.6                | 2.234  | 0.183                | 0.817               |

\*Drained weight

T<sub>0</sub> = Food temperature at beginning of thermal process

T<sub>1</sub> = Holding temperature of heating medium

P<sub>a</sub> = Pressure in pascal

t<sub>up</sub> = Come-up heating time

t<sub>b</sub> = Processing heating time

It is clear from eq. (1) that the proper values of  $z$ , the slope index of the thermal death-time curve of target microorganisms, and  $T_R$ , a reference temperature, should be chosen to estimate an  $F_p$  value. Since chili con carne and white rice are low-acid foods, target microorganisms for the thermal processing of both foods are Clostridium botulinum spores. Therefore, a standard  $z$  value of  $10^\circ\text{C}$  was used to estimate the sterilizing value. There was no published information available on the target microorganisms of peach slices in syrup. However, one reference book (Lopez, 1981) states bacteria (e.g., Clostridium pasteurianum, Lactobacillus sp., Leuconostac sp.), yeasts (only in case of gross underprocessing) or molds (Byssoschlamys fugtra) being the target factors for the thermal processing of high-acid foods. Another reference book (Tanikawa et al., 1969) states Saccharomyces cervisiae as the target factor for canned mandarin orange segments. The  $z$  values of these microorganisms are likely within the range between  $4.2^\circ\text{C}$  and  $12^\circ\text{C}$  according to reference books (Hugo, 1971; Samson et al., 1984). Therefore, these three  $z$  values were used to estimate the lethalties of peach slices in syrup:  $4.2^\circ\text{C}$ ,  $10^\circ\text{C}$  and  $12^\circ\text{C}$ . Note that  $10^\circ\text{C}$  was included for comparison purposes.

As for  $T_R$ ,  $121.11^\circ\text{C}$  (Celsius conversion of  $250^\circ\text{F}$ ) is commonly used to estimate  $F_p$  for the thermal processes of low-acid foods. It is a common practice to use a  $T_R$  below  $100^\circ\text{C}$  for high-acid food. However,  $121.11^\circ\text{C}$  was used as the  $T_R$  for peach slices for two reasons. First, an  $F_p$  based on  $T_R$  may be converted easily to another  $F_p$  based on another  $T_R$  by:

$$F_{p2} = 10^{(T_{r1}-T_{r2})/z} F_{p1} \quad (2)$$

where:  $F_{p2}$  = Subsequent sterilizing value

$T_{r2}$  = Subsequent reference temperature

Where secondly, one obtains final conclusions identical to those based on different  $T_r$  values if enough significant digits are retained in estimated  $F_p$  values. This may be easily accomplished through double precision computations.

#### Heat-Penetration Parameters:

Empirical heat-transfer parameters,  $f$  and  $j$  values, in packaged food were estimated from six temperature-history curves for each food, which were provided by the U.S. Army Natick RD&E Center. Parameters  $f$  and  $j$  may be determined from a curve obtained by plotting the common logarithmic of unaccomplished temperature differences against heating or cooling times. The unaccomplished temperature difference is a difference between surrounding heat exchange medium and food temperatures. A curve for conduction heated or cooled food normally consists of an initial curvilinear part and subsequent linear part. Parameters  $f$  and  $j$  are related to the slope and intercept of the linear part as shown below:

$$\log_{10} (|T_a - T|) = -t/f + \log_{10}[j(|T_a - T_i|)], \quad (3)$$

where:  $T_a$  = Temperature of surrounding heat exchange medium.

$T_i$  = Food temperature at the beginning of heating phase (identical to  $T_o$ ) or at the beginning of cooling phase.

The  $f$  and  $j$  values ( $f_h$  and  $j_h$ ) of a heating curve (a semilogarithmic temperature history in the heating phase of a thermal process) were estimated by using a computer program previously developed (Hayakawa, et al., 1981) after making a correction for come-up heating (Ball and Olson, 1957).

The  $f$  and  $j$  values ( $f_c$  and  $j_c$ ) of a cooling curve (a semilogarithmic temperature history in the cooling phase of a process) were determined through similar computations.

where:

$f_p$  =  $f$  value of rectangular parallelepiped (a brick shape)

$j_p$  =  $j$  value of rectangular parallelepiped

$f_L$  =  $f$  value of plate of thickness  $2L$

$f_W$  =  $f$  value of plate of thickness  $2W$

$f_H$  =  $f$  value of plate of thickness  $2H$

$j_L$  =  $j$  value of plate of thickness  $2L$

$j_W$  =  $j$  value of plate of thickness  $2W$

$j_H$  =  $j$  value of plate of thickness  $2H$

Conduction heat transfer in the food was assumed to examine the experimental temperature history curves as discussed later.

#### Temperature Response Properties of Peach Slices in Syrup

Principles of heat transfer were used to estimate the  $f$  and  $j$  values of peach slices in a syrup package with a layer of insulation material over its outside surface. To apply these principles, the inside space configuration of the container was approximated by a rectangular parallelepiped with a volume identical to the container.

The parameters  $f$  and  $j$  of a rectangular parallelepiped,  $2L \times 2W \times 2H$ , are related to respective heat-penetration parameters of infinitely wide plates of thicknesses  $2L$ ,  $2W$ , and  $2H$  according to the analysis of analytical conduction

formula as shown below (Pflug et al., 1965):

$$1/f_p = 1/f_L + 1/f_W + 1/f_H \quad (4)$$

$$j_p = j_L \cdot j_W \cdot j_H \quad (5)$$

The parameters  $f$  and  $j$  of an infinite plate may be estimated from the analytical formula when thermal diffusivity,  $\alpha$ , and Biot number,  $Bi_H$ , are available. For example, the  $f$  and  $j$  values of an infinite plate of thickness  $2H$  may be estimated by:

$$f_H = H^2 (\ln 10) / (p_{1H}^2 \alpha) \quad (6)$$

where  $H$  = one half of effective inside height of container whose shape is approximated by a brick shape.

$$j_H = j_{Hc} \cos (p_{1H} x / H), \quad (7)$$

where  $p_{1H}$  is the first positive root of the following equation:

$$p \tan p = Bi_H \quad (8)$$

$$\text{where } Bi_H = h H / k. \quad (9)$$

where  $h$  = overall coefficient for heat transfer from heat exchange medium to food surface.

In eq. 7,  $j_{Hc}$  is the  $j$  value on the center plane of the plate, which may be estimated by:

$$j_{Hc} = 2Bi_H \sec p_{1H} / \{Bi_H(Bi_H + 1) + p_{1H}^2\}. \quad (10)$$

From eqs. (8) and (10), one obtains,

$$1/f_p = (\alpha / \ln 10) \{ (L/p_{1L})^2 + (W/p_{1W})^2 + (H/p_{1H})^2 \}, \quad (11)$$

where  $p_{1L}$  and  $p_{1W}$  are the first positive roots of the following equations:

$$p_{1L}: \quad p \tan p = S_L Bi_H \quad (12)$$

$$p_{1W}: \quad p \tan p = S_W Bi_H \quad (13)$$

The temperature data were calculated at the center of each ration container. Therefore, the central  $j$  may be estimated from eqs. 4 and 9:

$$j_p = 8Bi_H^2 S_L \cdot S_W \sec p_{1W} \cdot \sec p_{1H} / [(S_L Bi_H (S_L Bi_H + 1) + p_{1L}^2) (S_W Bi_H (S_W Bi_H + 1) + p_{1W}^2) (Bi_H (Bi_H + 1) + p_{1W}^2)] \quad (14)$$

The values of  $Bi_H$  and corresponding first positive roots  $p_{1L}$ ,  $p_{1W}$ , and  $p_{1H}$  were determined by substituting an experimentally determined  $j$  value into eq. 14 (noting that there is only one unknown since all roots are related to  $Bi_H$  as shown by eqs. 8, 12, and 18). The effective thermal diffusivity  $\alpha$  of peach slices in syrup was estimated by substituting an experimental  $f_p$  value and the roots into eq. 11.

The effective thermal conductivity of the food,  $k$ , was determined from the definition of  $\alpha$  and the estimated density,  $\rho$ , and specific heat,  $C_p$ , of the food.

$$k = \alpha C_p \rho \quad (15)$$

The value of  $Bi$  is changed when a layer of insulation material is applied to all outside surfaces of a container since an effective, convective surface heat conductance is reduced from  $h$  to  $U$ , as seen by reducing eq.(9) by (16), leading to (17).

$$1/U = 1/h + I_n/k_n \quad (16)$$

$$Bi_{Hn} = UH/k \quad (17)$$

where:

$U$  = Overall coefficient for heat transfer through insulated container wall

$I_n$  = Insulation thickness

$k_n$  = Thermal conductivity of insulation

$Bi_{Hn}$  =  $Bi_H$  of insulation

For the present analysis, expanded polystyrene was chosen as an insulation material.

Equation 11 gives a relationship between the value of  $f$  for peach slices in an insulated container,  $f_{pn}$ , and  $f$  of those in a noninsulated container,  $f_p$ . The relationship follows:

$$f_{pn}/f_p = \frac{[(L/p_{1L})^2 + (W/p_{1W})^2 + (H/p_{1H})^2]}{[(L/p_{1Ln})^2 + (W/p_{1Wn})^2 + (H/p_{1Hn})^2]} \quad (18)$$

Similarly, a relationship between  $j$  values of peach slices in insulated and noninsulated containers is obtained from eq. 14, as below:

$$j_{pn}/j_p = f(Bi_{Hn})/f(Bi_H),$$

where:

$$f(Bi_H) = Bi_H^3 \sec p_{1L} \sec p_{1W} \sec p_{1H} / [(S_L Bi_H (S_L Bi_H + 1) + p_{1L}^2) (S_W Bi_H (S_W Bi_H + 1) + p_{1W}^2) (Bi_H (Bi_H + 1) + p_{1H}^2)]. \quad (20)$$

$f(Bi_{Hn})$  may be defined by replacing  $Bi_H$ ,  $p_{1L}$ ,  $p_{1W}$  and  $p_{1H}$  by  $Bi_n$ ,  $p_{1Ln}$ ,  $p_{1Wn}$  and  $p_{1Hn}$ , respectively.

For an assumed thickness  $I_n$ , of insulation material, a modified  $Bi$ ,  $Bi_{Hn}$ , was estimated by eqs. 14 and 15. Then constants  $p_{1Hn}$ ,  $p_{1Ln}$ , and  $p_{1Wn}$  were estimated by using eqs. 8, 12, and 13 ( $Bi_H$  in these equations was replaced by  $Bi_{Hn}$ ). The values of  $f_h$ ,  $f_c$ ,  $j_h$ , and  $j_c$  applicable to an insulated container package were estimated by using eqs. 18 and 19.

### Estimation of $F_p$ , A Function of $f$ and $j$ and of Other Process Conditions

A modified version of a computer program developed previously (Hayakawa, 1977) was used to estimate  $F_p$  values as a function of heat-penetration parameters,  $z$ -value, retort temperature, initial food temperature and other processing conditions. This program has an option of specifying either conductive or convective food being processed. Because of an assumption previously stated, the option of heat-conductive food was used for the present analysis.

### RESULTS AND DISCUSSION

Table 2 shows the target sterilizing values,  $F_p$ 's, estimated from the temperature histories of foods. The  $F_p$ 's of chili con carne and white rice are typical values for low-acid foods. The  $F_p$  of peach slices in syrup was highly dependent on the  $z$  value used. Since the temperatures of peach slices were below  $T_r$ , a smaller  $z$  value resulted in smaller values of integrand of eq. 1. Therefore, a smaller  $F_p$  value was obtained.

The examination of the temperature data used for the  $F_p$  estimation revealed that the temperatures of all three foods continued to increase during initial cooling periods. This implies that heat is transmitted mostly through heat conduction within these foods since there is no temperature increase during a cooling phase for convective heating of food. With chili con carne and white rice, this was expected since there were virtually no free liquids in these foods. With peach slices in syrup, there was a relatively small height profile of a container for peach slices, with an average inside height of 30 mm. This contributes to minimum convective flow of syrup within each container during a thermal processing. Based on the above observations, conduction heat flow within all foods was assumed as previously stated.



Table 2. Target Sterilizing Values ( $F_p$ ) of Three Products in Semirigid Containers

| Food                  | z Value ( $^{\circ}\text{C}$ ) | $F_p$ (sec.) |
|-----------------------|--------------------------------|--------------|
| Chili Con Carne       | 10.0                           | 450          |
| White Rice            | 10.0                           | 450          |
| Peach Slices in Syrup | 4.2                            | 0.00258      |
|                       | 10.0                           | 3.00         |
|                       | 11.9                           | 9.12         |

Table 3 shows the values of heat-penetration parameters and their standard deviations. Effective inside dimensions of the containers for the three selected foods are shown in Table 4. The dimensions of the containers for chili con carne and white rice are given as a comparison although they were not used for the present analysis.

#### Processes with Adjusted Initial Food Temperatures

The heating time,  $t_b$ , should be reduced for the low-acid food and increased for the high-acid food to accomplish the simultaneous processing of all foods at a common retort temperature. Therefore, the initial temperature,  $T_0$ , of white rice and chili con carne were adjusted between 29.4 and 82.2 °C and  $T_0$  of peach slices between 1.6 and 15.6 °C. Analyses were performed for two retort temperatures, 110.0 and 121.1 °C. The results are summarized in Table 5.

With the retort temperature of 110 °C, the  $t_b$ 's of both low-acid foods were reduced only slightly when their  $T_0$ 's were increased from 29.4 to 82.2 °C, about 9% reduction. It is of interest to note that the  $t_b$ 's of the two foods are nearly identical to each other although their  $f_h$  values differ. This is due to the fact that the  $f_c$  of white rice is considerably greater than the  $f_c$  of chili con carne. The larger  $f_c$  value resulted in higher food temperature during the cooling phase because of a slower rate of cooling. Therefore, there was a greater lethality in the cooling phase for white rice as compared to that of chili con carne; This cooling phase rate compensated for a smaller lethality for the heating phase of white rice.

Table 3. Heat-Penetration Parameters of Three Products in Army Ration Containers

| Parameters <sup>a)</sup> | Food                         |                |                            |
|--------------------------|------------------------------|----------------|----------------------------|
|                          | Chili Con Carne              | White Rice     | Peach Slices <sup>b)</sup> |
| $f_h$ (h)                | 0.441 (0.0053) <sup>c)</sup> | 0.471 (0.0058) | 0.305 (0.0104)             |
| $f_c$ (h)                | 0.596 (0.0185)               | 0.987 (0.0610) | 0.522 (0.0517)             |
| $j_h$                    | 1.235 (0.035)                | 1.375 (0.049)  | 1.170 (0.085)              |
| $j_c$                    | 1.209 (0.022)                | 1.431 (0.280)  | 1.170 (0.011)              |

a)  $f_h$  = Slope index of semilogarithmic temperature history curve of the heating phase of process.

$f_c$  = Slope index of semilogarithmic temperature history curve of the cooling phase of process.

$j_h$  = Empirical heat-penetration parameter related to the intercept of semilogarithmic temperature history curve of the heating phase of process.

$j_c$  = Empirical heat-penetration parameter related to the intercept of semilogarithmic temperature history curve of the cooling phase of process.

b) Values of packs in uninsulated containers.

c) Values in parentheses are standard deviations.

Table 4. Effective Inside Dimensions (mm) of Containers

| Container<br>for | Height<br>(2H) | Width<br>(2W) | Length<br>(L) |
|------------------|----------------|---------------|---------------|
| Peach Slices     | 30             | 70            | 118           |
| Chili Con carne  | 26             | 92            | 136           |
| White Rice       | 30             | 70            | 118           |

The  $t_b$ 's of peach slices are 15 to 20% of the  $t_b$ 's of the low-acid foods depending on the  $z$  value. The use of the smallest  $z$  value resulted in the longest  $t_b$ 's. The use of the largest  $z$  value gave the shortest  $t_b$ 's. There was no significant increase in  $t_b$  when the initial food temperature was lowered to 1.6 °C.

With the retort temperature of 121.1 °C, relative differences in the  $t_b$ 's of the low- and high-acid foods became less than those at the lower retort temperature, a 35 to 40% difference. There were relatively large reductions, 20%, in the heating times for low-acid food when the initial temperatures were increased. However, there were no significant increases in the high acid food heating times when the initial temperatures were lowered. The  $z$  values did not significantly influence the high-acid food heating times. It is clear from Table 5 that the simultaneous processing of all foods is not possible by adjusting the initial food to temperatures at both retort temperatures.

#### Application of Insulation on High-Acid Food Containers

An effective thermal diffusivity of peach slices in syrup was estimated as previously described, 2.07 mm<sup>2</sup>/sec (an average of six values,  $\pm$  10%). The specific heat,  $c_p$ , and density,  $\rho$ , of the food were required to estimate its thermal conductivity using eq. 15.

To obtain the named physical property values, the food was assumed to be equilibrated with a 15% sugar solution (mass basis). Therefore,  $c_p$  was estimated by using the Mollier chart of sugar solution (Burke, 1954), 3.81 J/(g°C). The same chart showed the refractive index,  $n$ , of the solution being 1.356. The density,  $\rho$ , of solution was estimated by using an empirical

Table 5. Predicted Heating Times of Three Rations of Different  $T_0$ 's and Different  $T_1$ 's<sup>1)</sup>

| $T_1 = 110^\circ\text{C}$ |                               |                             |                          | $T = 121.11^\circ\text{C}$ |                               |                             |                          |
|---------------------------|-------------------------------|-----------------------------|--------------------------|----------------------------|-------------------------------|-----------------------------|--------------------------|
| Food <sup>2)</sup>        | $T_0$<br>( $^\circ\text{C}$ ) | $Z$<br>( $^\circ\text{C}$ ) | $t_b$<br>$h(\text{min})$ | Food                       | $T_0$<br>( $^\circ\text{C}$ ) | $Z$<br>( $^\circ\text{C}$ ) | $t_b$<br>$h(\text{min})$ |
| C                         | 29.44                         | 10                          | 2.283(137.0)             | C                          | 29.44                         | 10                          | 0.746(44.74)             |
|                           | 37.78                         |                             | 2.262(135.7)             |                            | 37.78                         |                             | 0.727(43.64)             |
|                           | 65.56                         |                             | 2.167(130.1)             |                            | 65.56                         |                             | 0.690(38.97)             |
|                           | 82.22                         |                             | 2.078(124.7)             |                            | 82.22                         |                             | 0.581(34.87)             |
| R                         | 29.44                         | 10                          | 2.283(137.0)             | R                          | 29.44                         | 10                          | 0.761(45.65)             |
|                           | 37.78                         |                             | 2.277(136.6)             |                            | 37.78                         |                             | 0.741(44.48)             |
|                           | 65.56                         |                             | 2.177(130.6)             |                            | 65.56                         |                             | 0.658(39.50)             |
|                           | 82.22                         |                             | 2.082(124.9)             |                            | 82.22                         |                             | 0.585(35.11)             |
| P                         | 1.67                          | 4.2                         | 0.452(27.14)             | P                          | 1.67                          | 4.2                         | 0.295(17.69)             |
|                           | 4.44                          |                             | 0.450(26.99)             |                            | 4.44                          |                             | 0.294(17.61)             |
|                           | 10.00                         |                             | 0.445(26.68)             |                            | 10.00                         |                             | 0.278(16.67)             |
|                           | 15.56                         |                             | 0.427(25.62)             |                            | 15.56                         |                             | 0.275(16.49)             |
| P                         | 1.67                          | 10                          | 0.3485(20.91)            | P                          | 1.67                          | 10                          | 0.260(15.62)             |
|                           | 4.44                          |                             | 0.345(20.70)             |                            | 4.44                          |                             | 0.251(15.44)             |
|                           | 10.00                         |                             | 0.338(20.27)             |                            | 10.00                         |                             | 0.251(15.06)             |
|                           | 15.56                         |                             | 0.329(19.76)             |                            | 15.56                         |                             | 0.244(14.64)             |
| P                         | 1.67                          | 10                          | 0.364(21.86)             | P                          | 1.67                          | 11.96                       | 0.271(16.26)             |
|                           | 4.44                          |                             | 0.361(21.66)             |                            | 4.44                          |                             | 0.268(16.08)             |
|                           | 10.00                         |                             | 0.354(21.22)             |                            | 10.00                         |                             | 0.261(15.67)             |
|                           | 15.56                         |                             | 0.346(20.77)             |                            | 15.56                         |                             | 0.254(15.26)             |

1) Cooling water temperature was assumed to be  $12^\circ\text{C}$ .

2) C = chili con carne, R = white rice, P = peach slices.

formula correlating  $n$  and  $\rho$ , thus

$$\rho = 0.00452 (n^2 - 1) / (n^2 - 2) = 0.001060 \text{ g/mm}^3.$$

Therefore, from eq. 15, one obtains:

$$k = 2.07 \times 3.81 \times 0.001060 = 0.00836 \text{ W/(mm } ^\circ\text{C)}.$$

The thermal conductivity of expanded polystyrene was  $4.19 \times 10^{-5} \text{ W/(mm } ^\circ\text{C)}$ , according to the literature (anonymous, 1988). The effective thermophysical property values of peaches in syrup and the thermal conductivity of the insulation material were used to convert the experimentally determined  $f$  and  $j$  values of peach slices in syrup packaged in an uninsulated container to those in an insulated container, as previously described.

Proper thicknesses of expanded polystyrene layers on the peach container were estimated for the three different  $z$  values through many trial computations. The following two different sets of results were obtained:

1. Different initial temperatures, yielding virtually identical heating times, which satisfied the required, target lethalties; 2. Same initial temperature, yielding slightly different heating times, which satisfied the lethality requirement.

The estimated initial food temperatures, insulation thickness and processing times (heating time) are shown in Tables 6, 7, and 8. Table 6 shows that the simultaneous processing of all three foods is possible at  $120^\circ\text{C}$  with the insulation thickness of 1.23 mm when the peach- $z$  value is  $4.2^\circ\text{C}$ . Virtually identical processing times (heating times) were obtained when the initial food temperatures were  $18.3^\circ\text{C}$  for chili con carne,  $26.7$  for rice, and  $27.2$  for peach slices.

When the initial temperatures of all foods were equal to 23.9 °C, slightly different processing times at 120 °C resulted: 0.825 h for peach slices, 0.803 h for chili con carne, and 0.823 h for rice. Therefore, the three foods may be processed simultaneously for 0.833 h (50 min) since the differences in the heating times are less than 0.0167 h (1 min).

It should be noted that the estimated heating times are defined in terms of thermal processes with no come-up time. Therefore, a process with a come-up time has a longer heating time (time measured from an exhaust completion time). For example, if there is a 0.167 h (10 min) come-up time, a heating time counted from the beginning of the process is  $10 + 50 - 0.42 \times 10 = 55.8$  or 56 min (0.933 h) (Ball's correction used).

When the z value for peach is 10 °C, the estimated insulation thickness was 1.65 mm (Table 7). Required initial food temperatures for virtually same processing times were 18.3 °C for chili con carne, 23.1 for peach, and 26.7 for rice. When the initial temperatures of the three foods were set to 23.9 °C, the estimated processing times were 0.80 h (48.5 min) for chili con carne, 0.811 (48.7) for peach, and 0.823 (49.4) for rice. Therefore, all three foods, whose initial temperatures are set to 23.9 °C may be processed for 0.833 (50 min.) at 120 °C.

The results of simulations for the peach-z value of 11.9 °C are shown in Table 8. The required insulation thickness was 1.62 mm. The required initial temperatures for virtually the same processing times for chili con carne and rice are identical to those of the two previous peach-z values. The initial temperature of peach, 23.9 °C, is slightly above that for the peach-z of 10 °C.



Table 6. Simulation with an Insulated Peach Container and with Peach-z Being 4.2 C°

Different Initial Temperatures

|                |          | Chili<br>Con Carne | White<br>Rice | Peach<br>Slices                               |
|----------------|----------|--------------------|---------------|---|
| z              | (C°)     | 10                 | 10            | 4.2   |
| f <sub>h</sub> | (h)      | 0.442              | 0.472         | 1.00  |
| f <sub>c</sub> | (h)      | 0.596              | 0.9885        | 1.214   |
| j <sub>h</sub> |          | 1.23               | 1.375         | 1.054   |
| j <sub>c</sub> |          | 1.209              | 1.431         | 1.077   |
| T <sub>o</sub> | (°C)     | 18.33              | 26.67         | 27.22   |
| T <sub>l</sub> | (°C)     | 120                | 120           | 120   |
| T <sub>w</sub> | (°C)     | 11.7               | 11.7          | 11.7  |
| t <sub>b</sub> | [h(min)] | 0.818(49.098)      | 0.818(49.072) | 0.818(49.081)                                 |
| F <sub>p</sub> | [h(min)] | 0.125(7.5)         | 0.125(7.5)    | 7.17x10 <sup>-7</sup> (4.3x10 <sup>-5</sup> ) |
| I <sub>n</sub> | (mm)     | -                  | -             | 1.23  |

Same Initial Temperature

|                |          | Chili<br>Con Carne | White<br>Rice | Peach<br>Slices                               |
|----------------|----------|--------------------|---------------|---|
| z              | (C°)     | 10                 | 10            | 4.2   |
| f <sub>h</sub> | (h)      | 0.442              | 0.4272        | 1.002   |
| f <sub>c</sub> | (h)      | 0.596              | 0.988         | 1.214   |
| j <sub>h</sub> |          | 1.235              | 1.375         | 1.054   |
| j <sub>c</sub> |          | 1.209              | 1.431         | 1.077   |
| T <sub>o</sub> | (248C)   | 23.89              | 23.89         | 23.89   |
| T <sub>l</sub> | (°C)     | 120                | 120           | 120   |
| T <sub>w</sub> | (°C)     | 11.7               | 11.7          | 11.7  |
| t <sub>b</sub> | [h(min)] | 0.808(48.452)      | 0.824(49.431) | 0.825(49.468)                                 |
| F <sub>p</sub> | [h(min)] | 0.125(7.5)         | 0.125(7.5)    | 7.17x10 <sup>-7</sup> (4.3x10 <sup>-5</sup> ) |
| I <sub>n</sub> | (mm)     | -                  | -             | 1.23  |

When the initial temperature of all foods was 23.9 °C, the required processing time for peaches was 0.817 h (49.03 min), slightly longer than that for the peach-z of 10 C°. Again, all foods may be processed simultaneously for 0.833 h (50 min) at 120 °C when their initial temperature is 23.9 °C.

The above analysis is based on the assumption that there is no contact resistance between the insulation layer and outside surface of a peach container. Therefore, a thinner layer of insulation is required when there is significant contact resistance. Another assumption is that the thermal conductivity of expanded polystyrene does not change during processing. A thicker insulation layer will be required if there is an increase in the thermal conductivity owing to moisture permeation. Thus, a closed cell structure is necessary for insulation.

Some further suggestions for tray design are as follows: The tray should be thermoformed from a high temperature melting polymer or coextruded set of polymers. Among the suitable candidates are:

polypropylene

polyvinylidene chloride

nylon

ethylene-vinyl alcohol.

Insulation for the heat sensitive food components can be provided by a foamed plastic insert, such as foamed polypropylene. This may be best provided as a preformed and filled separate compartment insert designed to minimize heat transfer. Thermoforming should include both vacuum and plug assist since thick walls may be used. Consideration should also be given to the use of aluminum foil as an overwrap to extend shelf life when low-barrier plastics are used for the tray.

Table 7. Simulation with an Insulated Peach Container and with Peach-z Being 10 °C

Different Initial Temperatures

|                |           | Chile<br>Con Carne | White<br>Rice | Peach<br>Slices              |
|----------------|-----------|--------------------|---------------|------------------------------|
| z              | (°C)      | 10                 | 10            | 10                           |
| f <sub>h</sub> | (h)       | 0.442              | 0.472         | 1.234                        |
| f <sub>c</sub> | [h (min)] | 0.596              | 0.988         | 1.436                        |
| j <sub>h</sub> |           | 1.235              | 1.375         | 1.044                        |
| j <sub>c</sub> |           | 1.209              | 1.431         | 1.064                        |
| T <sub>o</sub> | (°C)      | 18.33              | 26.67         | 23.06                        |
| T <sub>l</sub> | (°C)      | 120                | 120           | 120                          |
| T <sub>w</sub> | (°C)      | 11.7               | 11.7          | 11.7                         |
| t <sub>b</sub> | [h(min)]  | 0.818(49.098)      | 0.818(49.072) | 0.817(49.023)                |
| F <sub>p</sub> | [h(min)]  | 0.125(7.5)         | 0.125(7.5)    | 8.33x10 <sup>-4</sup> (0.50) |
| I <sub>n</sub> | (mm)      | -                  | -             | 1.65                         |

Same Initial Temperatures

|                |          | Chili<br>Corn Carne | White<br>Rice | Peach<br>Slices               |
|----------------|----------|---------------------|---------------|-------------------------------|
| z              | (°C)     | 10                  | 10            | 10                            |
| f <sub>h</sub> | (h)      | 0.442               | 0.472         | 1.234                         |
| f <sub>c</sub> | (h)      | 0.596               | 0.388         | 1.436                         |
| j <sub>h</sub> |          | 1.235               | 1.375         | 1.044                         |
| j <sub>c</sub> |          | 1.209               | 1.431         | 1.064                         |
| T <sub>o</sub> | (°C)     | 23.89               | 23.89         | 23.89                         |
| T <sub>l</sub> | (°C)     | 120                 | 120           | 120                           |
| T <sub>w</sub> | (°C)     | 11.7                | 11.7          | 11.7                          |
| t <sub>b</sub> | [h(min)] | 0.808(48.452)       | 0.824(49.431) | 0.812(48.716)                 |
| F <sub>p</sub> | [h(min)] | 0.125(7.5)          | 0.125(7.5)    | 8.33x10 <sup>-4</sup> (0.050) |
| I <sub>n</sub> | (mm)     | -                   | -             | 1.65                          |

Table 8. Simulation with an Insulated Peach Container and with Peach-z Being 11.9 C°

Different Initial Temperature

|                         | Chili<br>Con Carne | White<br>Rice | Peach<br>Slices               |
|-------------------------|--------------------|---------------|-------------------------------|
| z (C°)                  | 10                 | 10            | 10                            |
| f <sub>h</sub> (h)      | 0.442              | 0.472         | 1.219                         |
| f <sub>c</sub> (h)      | 0.596              | 0.988         | 1.421                         |
| j <sub>h</sub>          | 1.235              | 1.375         | 1.045                         |
| j <sub>c</sub>          | 1.209              | 1.431         | 1.965                         |
| T <sub>o</sub> (°C)     | 18.33              | 26.67         | 23.89                         |
| T <sub>l</sub> (°C)     | 120                | 120           | 120                           |
| T <sub>w</sub> (°C)     | 11.7               | 11.7          | 11.7                          |
| t <sub>p</sub> [h(min)] | 0.818(49.098)      | 0.818(49.092) | 0.817(49.029)                 |
| F <sub>p</sub> [h(min)] | 0.125(7.5)         | 0.125(7.5)    | 2.08x10 <sup>-3</sup> (0.152) |
| I <sub>n</sub> (mm)     | -                  | -             | 1.62                          |

Same Initial Temperature

|                         | Chili<br>Con Carne | White<br>Rice | Peach<br>Slices               |
|-------------------------|--------------------|---------------|-------------------------------|
| z (C°)                  | 10                 | 10            | 11.96                         |
| f <sub>h</sub> (h)      | 0.442              | 0.472         | 1.219                         |
| f <sub>c</sub> (h)      | 0.596              | 0.388         | 1.421                         |
| j <sub>h</sub>          | 1.235              | 1.375         | 1.045                         |
| j <sub>c</sub>          | 1.209              | 1.431         | 1.065                         |
| T <sub>o</sub> (°C)     | 23.89              | 23.89         | 23.89                         |
| T <sub>l</sub> (°C)     | 120                | 120           | 120                           |
| T <sub>w</sub> (°C)     | 11.7               | 11.7          | 11.7                          |
| t <sub>p</sub> [h(min)] | 0.808(48.452)      | 0.824(49.431) | 0.817(49.029)                 |
| F <sub>p</sub> [h(min)] | 0.125(7.5)         | 0.125(7.5)    | 2.08x10 <sup>-3</sup> (0.152) |
| I <sub>n</sub> (mm)     | -                  | -             | 1.62                          |

The application of insulation material on the peach container introduces additional statistical variability in the process lethality. Therefore, a larger safety factor will be required for the simultaneous processing of the three foods.

#### CONCLUSIONS

Through the computer simulations, it was found that the simultaneous processing of the three foods in one sterilizer was not possible by adjusting their initial temperatures and holding the temperature of a heating medium. However, the simultaneous processing is possible when the peach container is insulated. The insulation thickness was slightly dependent on the peach-z value.

This document reports research undertaken at the US Army Natick Research, Development and Engineering Center and has been assigned No. NATICK/TR-46-1 in the series of reports approved for publication.

## GLOSSARY

|        |  |
|--------|--|
| Bi     | Biot number = $hl/k$ .   |
| $Bi_H$ | = $hH/k$ .   |
| $C_p$  | Specific heat of food.   |
| f      | Slope index of semilogarithmic temperature history curve.  |
| $F_p$  | Sterilizing value.   |
| H      | One half of effective inside height of container whose shape is approximated by a brick shape.                 |
| h      | Overall coefficient for heat transfer from heat exchange medium to food surface.                               |
| $I_n$  | Insulation thickness.  |
| j      | Empirical heat penetration parameter related to the intercept of semilogarithmic temperature history curve.    |
| k      | Thermal conductivity.  |
| L      | One half of effective inside side dimension of container whose shape is approximated by a brick shape.         |
| l      | Half thickness of a plate.   |
| n      | Refractive index.  |
| $P_1$  | First positive root of $p \tan p = Bi$ .   |
| $S_L$  | = $L/H$ .  |
| $S_W$  | = $W/H$ .  |
| T      | Temperature.   |
| $T_a$  | Temperature of surrounding heat exchange medium.   |
| $T_i$  | Food temperature at the beginning of heating phase (identical to $T_o$ ) or at the beginning of cooling phase. |
| $T_o$  | Food temperature at beginning of thermal process.  |

- $T_1$  Holding temperature of heating medium.
- $T_w$  Temperature of cooling water.
- $t$  Time.
- $t_1$  Heating or cooling time at the beginning of a linear part in semilogarithmic temperature history curve.
- $U$  Overall coefficient for heat transfer through insulated container wall.
- $W$  One half of effective, inside side dimension of container whose shape is approximated by a brick.
- $x$  Location variable. Distance measured from central plane of infinite plate.
- $z$  Slope index of thermal death time curve.
- $\alpha$  Thermal diffusivity.
- $\rho$  Density.
- $f( )$  Function defined by eq. 18.
- Subscript
- $b$  Processing phase of process (constant heating phase).
- $c$  Cooling phase of process.
- $end$  End of process (end of Cooling phase).
- $H$  Related to plate of thickness  $2H$ .
- $h$  Heating phase of process.
- $L$  Related to plate of thickness  $2L$ .
- $n$  Insulation.
- $p$  Rectangular parallelepiped.
- $r$  Reference value.
- $up$  Come-up heating.
- $1,2$  First and second values, respectively.

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| John F. Kennedy Special Warfare Center      |       |
| ATTN: ATSU-CD-TE                            | 1     |
| ATTN: ATSU-CD-ML-M                          | 1     |
| ATTN: DOCD-M-L                              | 1     |
| Fort Bragg, NC 28307-5000                   |       |
| <br>Commanding General                      | <br>1 |
| Warfighting Center                          |       |
| ATTN: Major Puckett                         |       |
| Marine Corps Combat Development Command     |       |
| Quantico, VA 22134-5080                     |       |
| <br>Program Manager, Combat Service Support | <br>1 |
| Marine Corps Research, Development and      |       |
| Acquisition Command                         |       |
| Washington, DC 20380-0001                   |       |
| <br>Commandant of the Marine Corps          | <br>1 |
| Headquarters Marine Corps                   |       |
| Code LFS-4                                  |       |
| ATTN: Major Gary Fuhrman                    |       |
| Washington, DC 20380-0001                   |       |
| <br>Commanding General                      | <br>1 |
| Fleet Marine Force-Atlantic                 |       |
| Norfolk, VA 23515-5000                      |       |
| <br>Commanding General                      | <br>1 |
| Fleet Marine Force-Pacific                  |       |
| Camp Smith, HI 96861-5000                   |       |
| <br>Commanding General                      | <br>1 |
| II Marine Expeditionary Force               |       |
| Camp Lejeune, NC 28542-5500                 |       |
| <br>Commanding General                      | <br>1 |
| Second Marine Division                      |       |
| Camp Lejeune, NC 28542-5500                 |       |
| <br>Commanding General                      | <br>1 |
| I Marine Expeditionary Force                |       |
| Camp Pendleton, CA 92055-5500               |       |
| <br>Commanding General                      | <br>1 |
| 1st Marine Division                         |       |
| Camp Pendleton, CA 92055-5500               |       |
| <br>Rutgers University                      | <br>1 |
| Cook College, Food Science Dept.            |       |
| ATTN: Kan-Ichi Hayakawa                     |       |
| New Brunswick, NJ 08903                     |       |